ALTERNATIVE FUELS and the ENVIRONMENT

Edited by

Frances S. Sterrett

LEWIS PUBLISHERS
Boca Raton Ann Arbor London Tokyo

Library of Congress Cataloging-in-Publication Data

Alternative fuels and the environment / edited by Frances Sterrett.
p. cm.
Includes bibliographical references and index.
ISBN 0-87371-978-6
1. Energy development—Environmental aspects. I. Sterrett, Frances S.
TD195.E49A44 1994
621.042—dc20 94-25419
CIP

Direct all inquiries to CRC Press, Inc., 2000 Corporate Blvd., N.W., Boca Raton, Florida 33431.

Lewis Publishers is an imprint of CRC Press

International Standard Book Number 0-87371-978-6
Library of Congress Card Number 94-25419
Printed in the United States of America 1 2 3 4 5 6 7 8 9 0
Printed on acid-free paper

Chapter 3

Total Fuel Cycle Emissions Analysis of Biomass-Ethanol Transportation Fuel

Cynthia J. Riley and K. Shaine Tyson

CONTENTS

ABSTRACT

In 1991, the U.S. Department of Energy (DOE) unveiled its National Energy Strategy (NES), a framework of policy initiatives to increase energy efficiency and reduce U.S.

dependence on imports and fossil fuels. The strategy endorsed a particular methodology, the total fuel cycle analysis (TFCA), as a tool to describe and quantify the environmental, social, and economic costs and benefits associated with energy alternatives. A TFCA should quantify inputs and outputs, their impacts on society, and the value of those impacts that occur from each activity involved in producing and using fuels. New fuels and energy technologies can be consistently evaluated and compared using TFCA, providing a sound basis for ranking policy options that expand the fuel choices available to consumers.

DOE has chosen ethanol produced from lignocellulosic biomass as a high-priority option for research and development. At the request of DOE, a fuel cycle analysis was completed to quantify the inputs and outputs of a hypothetical biomass-ethanol industry in the year 2010 that produces a 95% ethanol, 5% gasoline fuel product (E95). A comparison of the results to a similar study of reformulated gasoline (RFG) was made.

Five regional biomass-ethanol fuel cycles were examined to evaluate the impact of different energy crop mixes on the levels of inputs and outputs. The technology of producing ethanol from biomass was based on engineering designs, research trends, past industrial experience, and expert opinion. Projections of future crude oil mixes, refining product outputs, and organizational structure were used to characterize the future RFG industry. Each fuel cycle is represented by a flow chart of activities based on a model industry. From this, an inventory of inputs (electricity, chemicals, materials, etc.) and outputs (fuel, emissions, wastes, etc.) was created for each fuel cycle. Only the operational phase of the fuel cycles was examined. The industrial activities for each fuel cycle are divided into five stages: feedstock production, feedstock transportation, fuel production, fuel distribution, and end use. This convention is used to describe the fuel cycles and the results. The discussion of results focuses on the gaseous, solid, and liquid fuel cycle emissions because the major issues impacting fuel use today are the environmental implications.[1,2]

This chapter in an excerpt summary of selected results from the final study *Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline Fuels, Volume I.*[3]

The conclusions drawn from this study are:

- R&D in vehicle technology can produce substantial benefits in terms of reduced emissions because the majority of emissions are produced in the end-use stage.
- E95 fuel cycles can produce 90% less carbon dioxide (CO_2) emissions compared to the RFG fuel cycle.
- E95 fuel cycles produce less nitrogen oxides (NO_x), sulfur dioxide (SO_2), CO_2, and particulate matter (PM) than RFG, when emissions associated with electricity production are included in the fuel cycle analyses.
- Ethanol fuels can extend our fossil fuel resources in the transportation sector because they require much fewer fossil fuel resources per Btu of fuel to produce.
- This study can be used to rank fuels based on selected criteria, such as CO_2 emissions, but impact and valuation analyses are required to conclude that one fuel is preferred to another.

INTRODUCTION

The National Energy Strategy (NES) presents a road map of policies that could lead to reduced dependence on imported fuels, more efficient use of domestic resources, economic growth, and a cleaner environment. To help reach these goals, the NES recommended the total fuel cycle analysis (TFCA) as the methodology for the U.S. Department of Energy (DOE) and its agencies to use for evaluating fuels and energy technologies.

One of the specific options identified by DOE is "Enhanced Transportation Biofuels Production R&D," which proposes to accelerate the research and development of biofuel technologies in the hope that they may become commercial sooner, and thus provide more benefit to the American public. DOE's Office of Energy and Efficiency and Renewable Energy (DOE/EERE), which funds biofuels technology development, wanted to enhance its capability to conduct credible evaluations of alternative fuel options by applying TFCA to biomass-ethanol and RFG fuels. This chapter summarizes the findings of the TFCA for these fuels. The information presented here is an excerpt summary of selected results from the final study *Fuel Cycle Evaluations of Biomass-Ethanol and Reformulated Gasoline Fuels, Volume I and II.*[4]

These fuel cycle analyses focused on measuring the amounts of inputs and outputs produced by two transportation fuels: E95, a blend of ethanol and 5% gasoline, and RFG. The ethanol is made from lignocellulosic feedstocks, trees, and grasses, using an experimental technology. Ethanol made from grain is not discussed. The time frame for the analyses is 2010.

The fuel cycles examined are snapshots in time. Technology and industry are constantly changing. The technologies used to model the biomass-ethanol industry represent researchers' best assumptions about how this industry might function. These fuel cycle analyses focused on measuring the inputs and outputs of two fuel cycles, similar to a mass and energy balance. This report provides the information necessary to rank fuels by specific criteria, such as CO_2 emissions. This report also provides the information required to conduct impact studies, but does not include impact studies or estimates of the costs associated with impacts.

These fuel cycle analyses provided a number of benefits:

1. Helped formulate future research agendas to answer questions that arose during this study and to provide data that did not exist for this study
2. Organized existing information
3. Improved the existing engineering design for biomass-ethanol production
4. Created a better understanding of how the biomass-ethanol industry may operate
5. Created a database of emissions for site-specific impact studies
6. Established a basis for future cost-benefit studies

The remainder of the report consists of several sections. The following subjects are discussed: 1) the TFCA methodology and its implementation (including the rationale behind the choices of fuels evaluated); 2) the industrial systems and technologies used to produce, deliver, and utilize the fuels; 3) the findings of the analysis; and 4) the conclusions drawn from the analysis and their implications.

TOTAL FUEL CYCLE ANALYSIS METHODOLOGY

TFCA provides a systematic approach for evaluating fuel resources and technologies. The fuel cycle analysis is determined by the following tasks:

1. Define the fuels or fuel cycles to be analyzed.
2. Define the fuel cycle boundaries that will limit the analysis.
3. Define the types of fuel cycle impacts to be analyzed (social, economic, technological, and environmental).

The following discussion of boundary conditions and assumptions is critical to understanding how the results provided should be used and for understanding the lessons learned from applying TFCA.

FUEL CYCLES

The two transportation fuels for the fuel cycle study are:

- E95, 95% ethanol manufactured from energy crops, trees, and grasses, with 5% gasoline added as denaturant in 2010.
- Reformulated gasoline (RFG) with methyl tertiary butyl ether (MTBE) in 2010.

These fuels were chosen because of their prominence in policies proposed by DOE and the Environmental Protection Agency (EPA).

Producing ethanol from lignocellulosic biomass is not a commercial technology today. However, by 2000 a number of facilities could be operating using low-cost feedstocks such as municipal solid waste (MSW) and by 2010, cellulosic crop technologies (often referred to as energy crops) should be commercially available. In addition, the biomass-ethanol industry will rely on energy crops as its primary source of feedstock because the unused supply of cellulosic waste materials may dwindle as demand for these materials increase (recycled paper, electric power, ethanol, etc.). The ethanol referred to in this study is produced from lignocellulosic biomass (such as trees and grasses), using an experimental technology. Ethanol from grain is not discussed.

The NES projected that nearly all gasolines will be reformulated by 2000 (U.S. DOE 1991 b). RFG using MTBE was selected because it is the most common RFG produced today.

The CAAA of 1990 requires the use of RFG containing oxygenates (Title II), and clean fuels in fleets in serious, severe, and extreme ozone nonattainment areas and in serious carbon monoxide (CO) nonattainment areas. Deadlines for adopting and using these fuels depend on the specific area and fuel considered. Specific clean fuels are not mandated but several alternative fuels are listed, including natural gas, methanol, ethanol (if the methanol and ethanol content of the fuel equals or exceeds 85% by volume), electricity, liquefied petroleum gas, RFG or reformulated diesel, and hydrogen.

The CAAA requires all fuels in the year 2000 to meet CAAA Tier I standards in motor vehicles (Title II, Section 203). By 2010, Tier II standards will be promulgated with stricter limitations on air emissions from vehicles. Cleaner burning fuels will be required and ethanol is listed in the CAAA as a clean fuel alternative. Thus, the fuel cycle for 2010 assumes that ethanol is produced from energy crops and is consumed as a denatured fuel in dedicated ethanol vehicles.

E95 is ethanol denatured with 5% gasoline; neat ethanol has to be denatured according to existing regulations of the Bureau of Alcohol, Tobacco and Firearms, to control the collection of taxes on alcohol purchased for consumption and to discourage human consumption of fuel ethanol. Gasoline is a common denaturant today, although other denaturants are available.

Both fuels are consumed by light-duty passenger vehicles. E95 is consumed in dedicated ethanol vehicles with optimized technology; dedicated ethanol vehicles are assumed to be available by 2010, according to the NES and other industry sources. In 2010, ethanol vehicles are projected to get 28.25 miles per gallon (mpg) and RFG vehicles are projected to get 35.6 mpg. The results of this study—the fuel cycle inventories—are presented in grams or gallons of outputs for every mile traveled by a light-duty passenger vehicle.

The data inventory was managed by the Total Emission Model for Integrated Systems (TEMIS). TEMIS is an accounting tool and does not optimize or project variables. It does allow for a wide array of sensitivity analyses by altering major parameters such as engine efficiencies or crop yields to determine the effects on the total inventories. The input and output characteristics of each activity in the fuel cycle and the magnitude of the activity are part of the basic database. TEMIS is used to link the various activities and adjust the relative magnitudes of the activities to reflect a consistent basis for the evaluation.

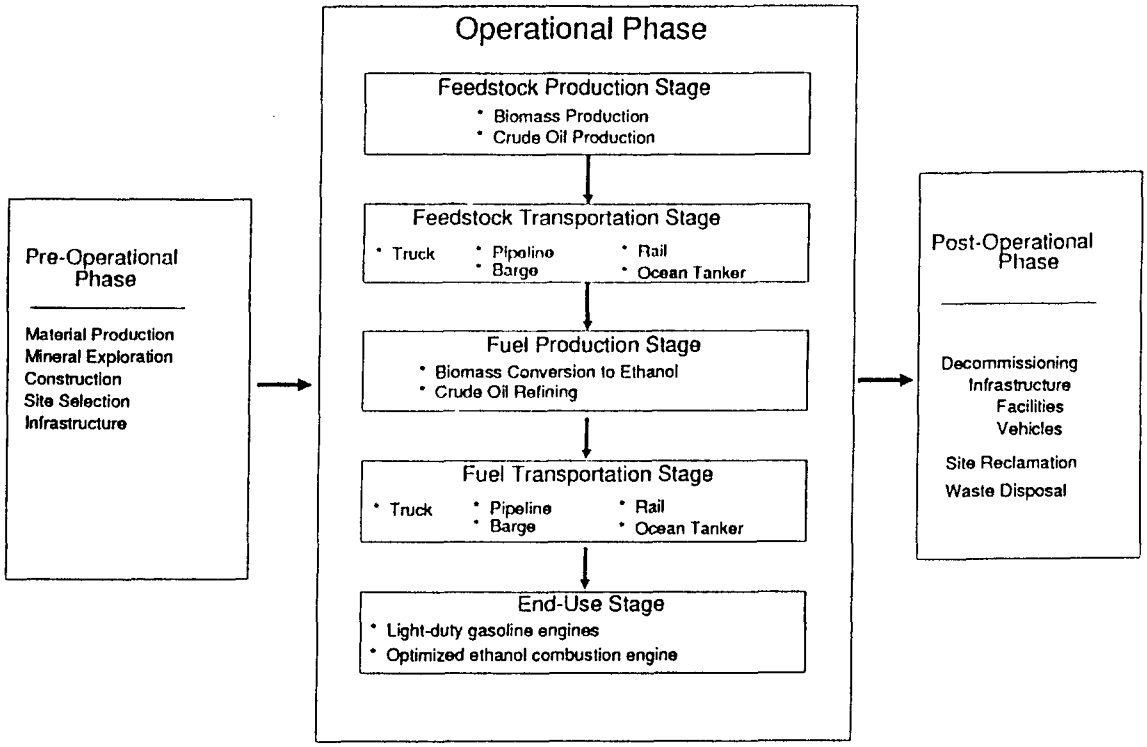


Figure 1 Fuel cycle boundaries.

No attempt was made to optimize technologies or markets represented by the fuel cycles based on economic or social criteria. Future economic parameters, such as costs and profits, will be affected by environmental issues, costs of environmental controls, and regulations. The industry structure examined is reasonable given what we know today about existing or similar industrial structures.

FUEL CYCLE BOUNDARIES

Only the operational phase of a fuel cycle (e.g., activities directly associated with producing and consuming the fuels) is documented in this study (Figure 1). Emissions associated with construction and decommissioning of the infrastructure required to produce, deliver, or consume the fuels are not included in the inventories. Drilling and other activities associated with exploration for crude oil were not included in the fuel cycle analysis because these activities are generally one-time occurrences that resemble construction and development more than daily operational activities.

A number of previous studies were examined to determine the effect of excluding pre- and post-operational phases. Deluchi (1992) constructed ethanol and RFG fuel cycles to estimate energy consumption and greenhouse gas emissions. His analysis showed that 10 to 15% of the total energy inputs of the fuel cycles are used in the production of the materials used in construction of the infrastructure and the vehicles.

Deluchi assumed that 2 to 3% of the energy content of the end-use fuel is used in exploration, production, and drilling for onshore and offshore oil. The DOE Handbook (1983) estimates that the energy used to produce on-shore oil in the lower 48 states is 1.5% of the energy in the crude produced, with about half of that used in development drilling and half used for oil production.

The exclusion of construction activities may be a significant issue but would require more information on future biomass-ethanol industrial development than is currently available. The future size and location of the biomass-ethanol industry has yet to be established and is controversial. This study was limited to the operational phase because it can be defined based on engineering principals and published information.

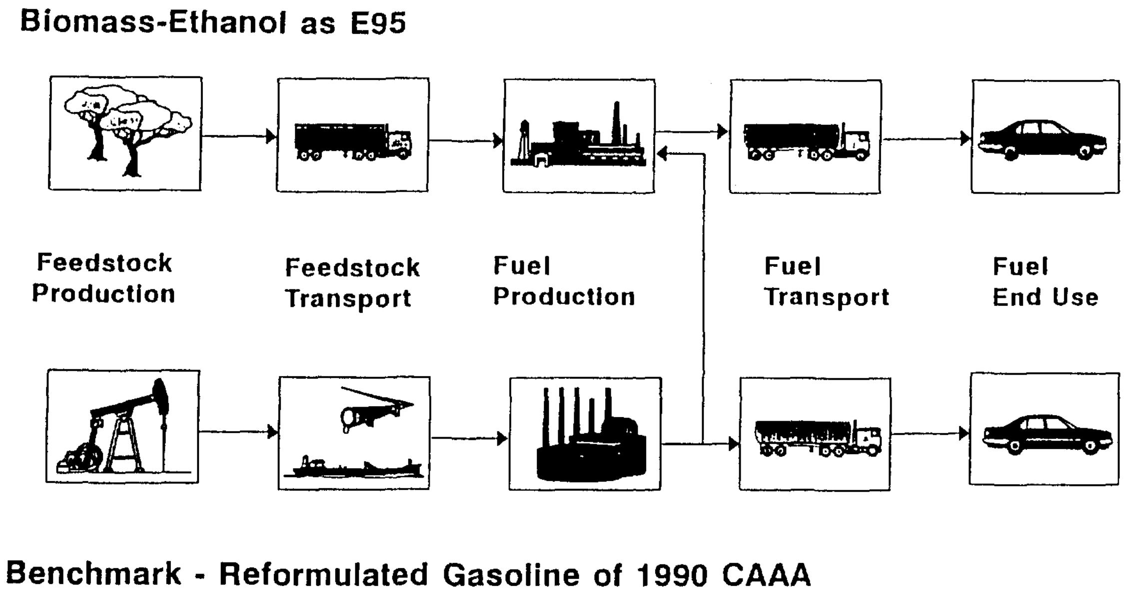


Figure 2 Fuel cycle stages.

The operational phase of the fuel cycle is divided into five stages: feedstock production, feedstock transportation, fuel production, fuel distribution, and end-use, which is primarily the combustion of fuels in light-duty passenger vehicles (Figure 2). Table 1 summarizes the major activities included in each stage of the fuel cycles examined in this report. Figure 3 provides a flow diagram for each of the two fuel cycles, showing how the outputs from one activity become the inputs to the next. The results reported later in this document have been allocated between co-products. The descriptions of the fuel cycles go into detail on allocation assumptions.

This study uses a three-part approach to evaluate a fuel cycle: (1) present detailed descriptions of the engineering systems that produce, transport, convert, and consume feedstocks and fuels; (2) construct a model industry that incorporates the activities defined in 1; and (3) build inventories of inputs and outputs for the fuel cycles. Estimates of fuel cycle inputs and outputs are based on theoretical engineering designs of the fuel cycles studied. The future petroleum industry is assumed to be nearly identical to the existing petroleum industry. The biomass-ethanol industry is created from a hypothetical set of assumptions based on existing agricultural practices, transportation infrastructure, and engineering designs. Outputs include estimates of air pollutants, solid wastes, water effluent, and energy products such as fuel, electricity, and heat. Inputs include labor, electricity, feedstocks (crude oil and biomass), chemicals, water, fuels, and equipment.

Six individual fuel cycles were created. These cases consist of five energy crop-E95 fuel cycles and the RFG fuel cycle (Table 2). The fuel cycle scenarios are limited to characterizing the domestic industry, although the RFG fuel cycle includes imported crude oil.

Five sites for biomass-ethanol production were chosen to reflect characteristics found in the surrounding regions (Figure 4). Regional variation in energy crop production inputs and outputs is very likely. Climate, soil characteristics, and other natural parameters affect which crops are produced, their yields, and agronomic practices, and thus affect the level of inputs and outputs of biomass production. Different mixes of energy crops affect the yield of ethanol, and thus affect the inputs and outputs of the fuel production stage. The five sites selected are: Peoria, IL; Lincoln, NE; Tifton, GA; Rochester, NY; and Portland, OR. Biomass production and conversion (fuel production) are located in the vicinity of these cities. Fuel was assumed to be consumed in the local area surrounding these cities.

Table 1 **Fuel cycle stages and activities**

Fuel Cycle Stage	E95	RFG
Feedstock production	Prepare land for planting; plant, tend, and harvest biomass crops and store on farm. Biomass crops: perennial grasses annual grasses short rotation trees	Crude oil production from domestic sites, on-site processing and storage; imported crude oil production same as domestic. By-products: natural gas
Feedstock transportation	Load biomass into trucks, rail, or barge for transportation to ethanol conversion facility; unload.	Transport crude oil via truck, pipeline, barge, and tanker in U.S. boundary waters to storage facilities; store; deliver crude to refineries via pipeline, barge, and tanker; unload and store at refinery.
Fuel production	Lignocellulosic crops converted to E95 using 2010 technology. Gasoline fuel cycle inventory included (5% denaturant) in this stage. By-product: electricity	Crude oil converted to reformulated gasoline and other products. MTBE production is excluded; MTBE is treated as input. By-products: non-gasoline products
Fuel distribution	E95 stored at conversion plant, loaded into railcars, transported to dedicated bulk tanks in bulk terminals at major metro areas in region and unloaded, loaded into tank trucks and delivered to retailers, unloaded and stored at retail facilities, pumped into dedicated vehicles.	Reformulated gasoline is transported in pipelines, barges, tank trucks, and tankers to bulk terminals, stored, loaded into tank trucks for retail delivery, unloaded into retail storage, and pumped into passenger vehicles.
End use	Combustion in a light-duty passenger car, dedicated ethanol engine.	Combustion in a light-duty passenger car, conventional gasoline engine.

In the RFG fuel cycle, we have assumed that imported crude has the same production emission characteristics as domestic crude oil production. This assumption can overestimate or underestimate actual inputs and outputs associated with international oil production, but the scope of estimating actual values was beyond this study. The emissions from transporting imported crude from the 200-mile economic trade boundary to U.S. ports are included but not the emissions that occur before the oil reaches the 200-mile boundary. The lack of readily available data and the modeling requirements involved to simulate crude oil transportation limited the treatment of this activity. The location and volumes of domestic crude oil production were taken from NES projections; refining and fuel

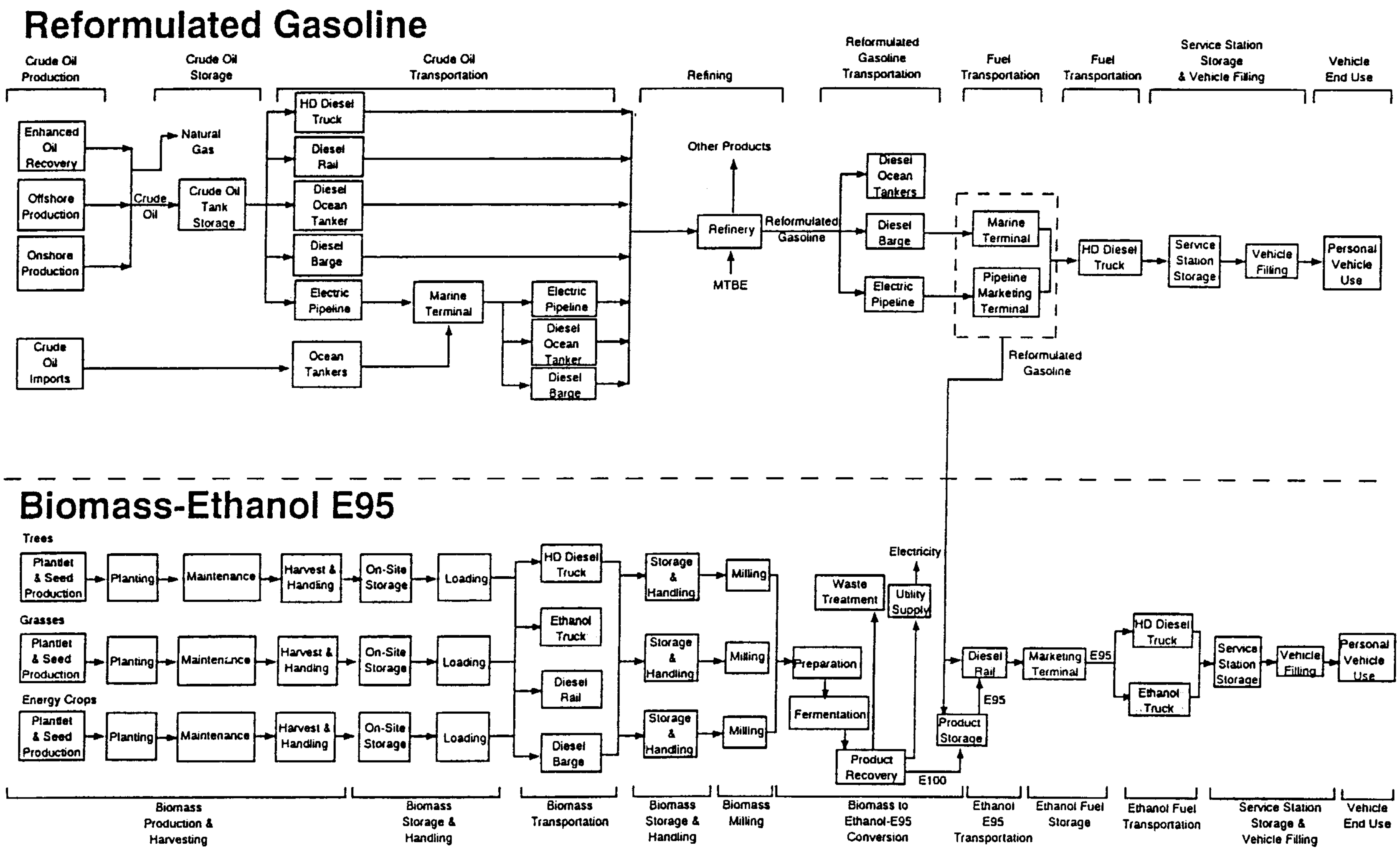


Figure 3 Fuel cycle activities.

Table 2 **Descriptions of fuel cycle cases**

Year	Descriptions
2010	RFG with inputs/outputs of crude oil production, transportation, and refining allocated between RFG and other products. Imported crude oil is assigned the same inputs/outputs as domestic crude oil production.
2010	E95 from Tifton biomass, includes inputs/outputs of the RFG case for the 5% gasoline content. Feedstock conversion, transportation, and production characteristics allocated between ethanol and electricity products.
2010	E95 from Peoria biomass, includes inputs/outputs of the RFG case for the 5% gasoline content. Feedstock conversion, transportation, and production characteristics allocated between ethanol and electricity products.
2010	E95 from Lincoln biomass, includes inputs/outputs of the RFG case for the 5% gasoline content. Feedstock conversion, transportation, and production characteristics allocated between ethanol and electricity products.
2010	E95 from Portland biomass, includes inputs/outputs of the RFG case for the 5% gasoline content. Feedstock conversion, transportation, and production characteristics allocated between ethanol and electricity products.
2010	E95 from Rochester biomass, includes inputs/outputs of the RFG case for the 5% gasoline content. Feedstock conversion, transportation, and production characteristics allocated between ethanol and electricity products.

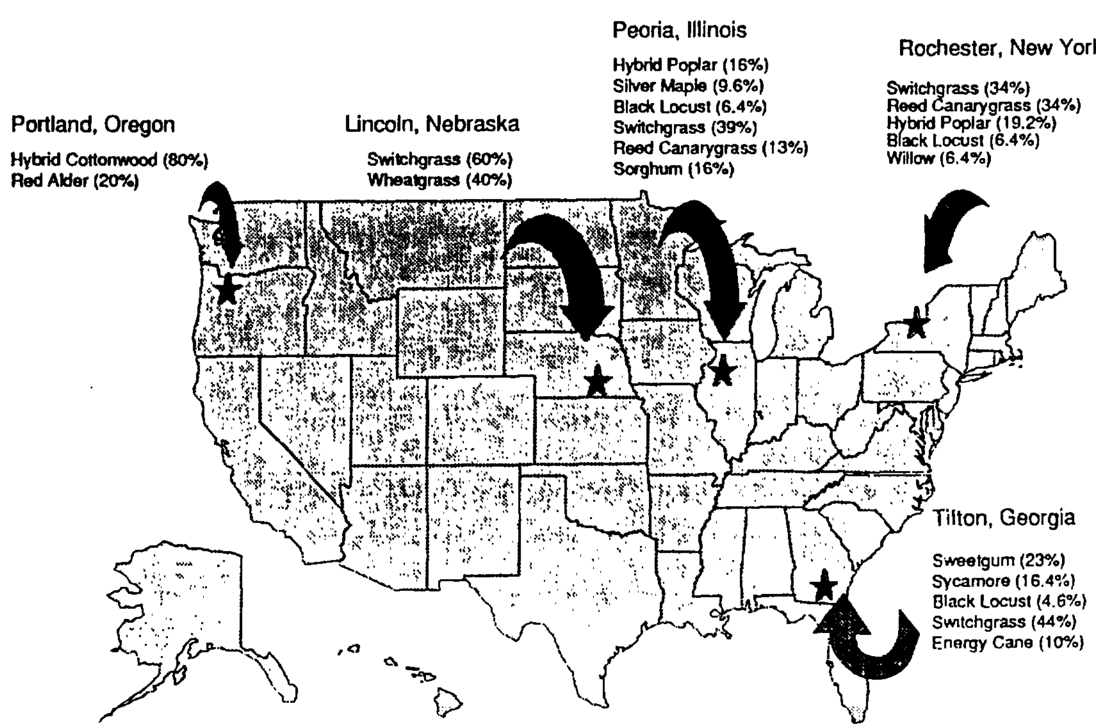


Figure 4 Ethanol fuel cycle locations.

consumption are assumed to be similar to patterns that exist today. All biomass and ethanol production is assumed to occur in the U.S.

FUEL CYCLE SCENARIOS

This section summarizes the major activities of the fuel cycles.

BIOMASS-ETHANOL FUEL CYCLES

The five biomass-ethanol scenarios are differentiated by feedstock and location. The feedstocks and plant locations are designed to bracket a range of potential scenarios that could lead to variations in environmental outputs from feedstock production, transportation, and conversion. The only difference between the scenarios is the choice of feedstock, such as blends of dedicated energy crops.

Each bioethanol production facility was assumed to require 1814 dry metric tons (2000 short tons) of feedstock per day to provide consistent capacities for comparative purposes. The ethanol plants produce between 295 and 320 million liters (78 and 85 million gallons) per year of E95. The ethanol yields varied according to feedstock composition. Fuel distribution varies between cases; ethanol fuels are distributed among regional cities based on a weighted average of population distribution in the region.

The feedstock production and transportation stages of the fuel cycle are described first, followed by a summary of biomass-ethanol conversion and fuel distribution.

Dedicated Energy Crop Supply

Biomass production, transportation, conversion, fuel distribution, and end-use were assumed to occur in the vicinity of the five locations selected. Biomass crops produced at each location were selected based on soil characteristics, climate, harvesting time schedules, storage characteristics, and available data from field trials. Data from field trials were projected to year 2010 based on recent trends. These projections involved yield estimates, input requirements, and cultural practices possible by year 2010. Researchers assumed that farmers will be employing more low-impact, environmental practices by 2010.

Crop establishment, cultural management, harvesting, and storage operations vary among the three broad classes of cellulosic energy crops: woody crops, perennial herbaceous crops, and annual herbaceous crops. Farmers in different regions were assumed to use similar practices for each type of crop.

The land available for energy crop production includes the counties within a 100-mile radius of each of the five ethanol manufacturing facilities, with the conversion facilities located in the approximate center of the areas. The total acreage used for energy crops is limited to a maximum of 7% of the suitable land across all land quality designations. This assumption would make energy crop production the fifth most important crop in each area and minimizes land competition.

Energy crop yields were expected to grow over time as scientists select and breed energy crops for desirable traits, and hybridize and propagate exceptional plant material (genetic research). Moreover, breeding superior crops is also expected to reduce management requirements; faster growth will reduce the frequency of weed control, and greater tolerance to stresses will reduce the need for pest control. Estimates of future yields were solicited from energy crop researchers in several regions. These estimates are based on expert opinion and are believed to be conservative. Soil conservation practices (such as reduced tillage methods) are assumed to be sufficiently advanced so that biomass crops maintain high survival rates and yields. Reduced tillage will minimize soil erosion in the early years of tree crop establishment and will reduce soil losses associated with annual crops.

A unique characteristic of energy crop production systems is that through photosynthesis they capture carbon dioxide from the atmosphere, release oxygen, and convert much of the carbon to useable energy feedstocks. Some of the carbon sequestered is returned to the atmosphere through the decomposition of a portion of the biomass harvesting residues, storage losses, leaf litter, and small roots that die each year. Some of the carbon initially captured by the growing biomass accumulates as organic matter in the soil until an equilibrium condition is reached, which may take 30 to 50 years. The net change of carbon in the soil and in above-ground tree stems and branches represents pools of carbon that are "sequestered" or removed from the atmosphere for relatively longer periods of time; thus, they represent a benefit of the biofuels system.

Harvested energy crops are stored on the farm until they are transported to an ethanol facility. Trees and thin-stemmed grasses are baled and can be stored covered or uncovered. Thick-stemmed grasses are harvested as forage and stored in silage facilities. Varying harvest schedules allow energy crops to be delivered to the ethanol facility year-round, minimizing conflicts with local demands for harvesting equipment and labor. Storage losses are accounted for in the transportation stage of the fuel cycle. Transportation distances depend on the distribution of cropland, geography, and available routes. In some cases, bulk commodity transportation modes (such as rail and barge) are available, while other sites rely exclusively on truck transportation.

Ethanol Production

The conceptual design for the lignocellulosic biomass-to-ethanol production process is based on research and process development work sponsored by the DOE Biofuels Program. The major drawback in this design is the lack of actual experimental data that would support the estimates of processing inputs, system efficiency, and system outputs. The inventory characteristics used in this study are the result of a mass and energy balance. Experimental data are used for specific assumptions or to model specific processes; however, the effects of running the process on a totally integrated basis (i.e., running all the process steps in series using effluent from one step as the feed to the next step) is uncertain.

Feedstock compositions and the material and energy balance consequences cause the major differences among the five cases. The compositions of the various energy crops were estimated based on data from the literature.

Energy crops enter the plant and are stored and processed in the feedstock handling area. After size reduction, the biomass is treated with a dilute sulfuric acid solution. This step increases the digestibility of the cellulose fraction and hydrolyzes the hemicellulosic fraction into sugars. This solution is neutralized and prepared for fermentation. Enzymes are used to hydrolyze the cellulose into glucose; then, microorganisms ferment the sugars to ethanol and carbon dioxide. The hydrolization and fermentation is combined into one system, called the "simultaneous saccharification and fermentation process," which is the foundation of this engineering design. Other designs are possible, and each different design would produce different fuel cycle inventories.

Ethanol produced from the fermentation steps is recovered, dehydrated, denatured with 5% (by volume) gasoline, and sold as fuel grade ethanol (E95). The fuel cycle inventory associated with gasoline production is added to the ethanol inventories in this stage. Thus, inventory characteristics for the ethanol production stage include full fuel cycle inventory characteristics for gasoline.

Solid wastes from fermentation and ethanol recovery are dewatered and sent to a fluidized bed boiler where high-pressure steam is generated. The recovered solids are mostly lignin and insoluble protein that entered the plant as part of the feedstock. These components have substantial heating value and are a major source of fuel for the boiler. Other liquid and gaseous waste streams are also sent to the boiler for energy recovery. The

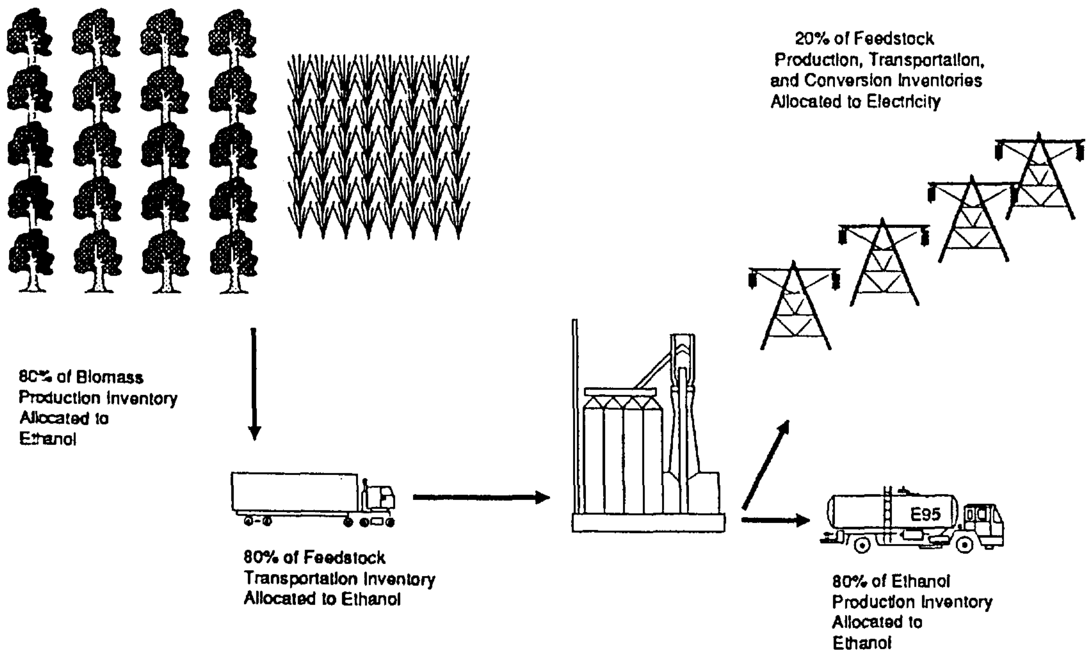


Figure 5 E95 fuel cycle allocation diagram.

high-pressure steam is let down through a steam turbine, which generates electricity for the plant and provides lower pressure steam for internal process users. Excess electricity is produced and sold to the local utility grid. The capacity of the cogeneration facilities ranges from 13 to 21 MW.

Liquid separated from the solids after ethanol recovery is processed in a wastewater treatment system. The wastewater is assumed to be treated to the standards required for industrial wastewater pretreatment; effluent is assumed to be sent to a publicly owned treatment works (POTW) facility. The exact nature of the effluent is unknown, although it is believed to be substantially similar to effluent from corn-ethanol plants.

Ash and uncombusted material from the boiler is recovered as a solid waste that requires disposal. It is assumed to be nonhazardous and therefore suitable for disposal in a licensed landfill. The ash should be similar to ash from power plants fired by wood and agricultural residues.

For each of the cases evaluated, a detailed material and energy balance was estimated, complete with utility summaries and chemical summaries. In all cases, the biomass production, transportation, and conversion inventory inputs and outputs were divided between two products: ethanol and electricity. Although this apportionment varied in each case, on the average 80% of all the inputs and outputs of the conversion stage and the previous stages was allocated to the ethanol product, and 20% was allocated to the electricity product (Figure 5). Similar methodology is used for the refinery allocation in the reformulated gasoline scenarios to account for the fact that multiple products are derived from crude oil.

Ethanol Fuel Distribution

We have assumed that the gasoline transportation and storage facilities could be used for ethanol with minor modifications. To simplify the types of transportation available and types of fuels used in them, all locomotives and trucks are assumed to be identical and use #2 diesel fuel. Fuel pumps at bulk facilities and retail terminals are assumed to be all electric. While we recognize that the industry is more complex and uses a variety of equipment and fuels, these simplifications were necessary for this analysis. Transportation mode efficiencies are based on published statistics. Vapor losses from storage tanks are based on an assumption of uniform tank design and size. All storage tanks and tank cars are equipped with vapor recovery systems to reduce volatile organic compounds (VOC) emissions.

The distribution stage begins at the ethanol plant when the E95 is loaded onto rail cars. The ethanol plants are located in regions that support a railroad infrastructure, allowing the E95 fuel to be transported to the surrounding major cities by rail. The rail cars unload the E95 at bulk storage plants located at or near the rail line in major cities located in a 200-mile radius around the ethanol plant. E95 from the bulk plant is loaded into tank trucks and delivered directly to retail stations. The average truck travels 50 miles round-trip between the bulk plant and the retail stations. Finally, E95 is unloaded into retail or commercial storage tanks, where it is pumped on demand into customers' cars.

REFORMULATED GASOLINE FUEL CYCLE

The NES assumes that RFG will be the primary fuel used by the year 2000. The RFG fuel cycle constructed for this study assumes that the future gasoline industry is substantially similar to the gasoline industry today. The RFG in these fuel cycles has a composition that is consistent with CAAA standards for an RFG containing 2% oxygen by weight. MTBE is the oxygenate used in the RFG fuel cycle. This fuel cycle study assumes that RFG based on MTBE is the only gasoline produced by the petroleum industry despite contrary projections. We did not attempt to model the future petroleum industry with all of its infinite variations.

The NES provides a recent forecast of the petroleum oil industry for the year 2010. The strategy scenario, used for this fuel cycle study, includes advances in petroleum production and utilization technologies and enough information to construct hypothetical slates of crude oil qualities and refinery characteristics.

Crude Oil Production

Crude oil production begins with the wellhead. Exploration and drilling are assumed to be pre-operation activities and are not included in this analysis. Conventional crude oil production technology will remain essentially similar to current technologies through the year 2010. Speculative resources, such as oil shale or gas hydrates, are not included because their economic exploitation is considered unlikely by 2010, given the expected economic conditions and anticipated technological development. The NES assumption that controversial resources, such as the Arctic National Wildlife Refuge and Outer Continental Shelf areas, will be developed and producing by 2010 is incorporated into this analysis.

The techniques that produce crude oil vary according to the properties of the crude, the geology of the underground reservoir, the age of the field, and its location (onshore, offshore). Most of the current domestic production of crude oil is from onshore oil fields using primary recovery technologies. However, these methods are expected to shift toward secondary and tertiary techniques as fields age. Secondary and tertiary techniques are more energy intensive than primary methods and employ gases, steam, and mechanical means of enhancing the flow of crude oil from the reservoir as the field becomes depleted. By 2010, heavier crudes will be produced, and secondary and tertiary production methods will account for a larger portion of the total production. Thus, the characteristics of the hypothetical blend of crude oils available to refineries and the inputs and outputs associated with crude oil production are projected to change over time.

The inputs and outputs associated with crude oil production are allocated between the two co-products produced from a wellhead—natural gas and crude oil—on a contained-Btu basis (Figure 6). Thus, only 58% of the emissions created during crude oil production are assigned to the crude oil that is transported to the refinery. See the refining description for a discussion of other allocation assumptions.

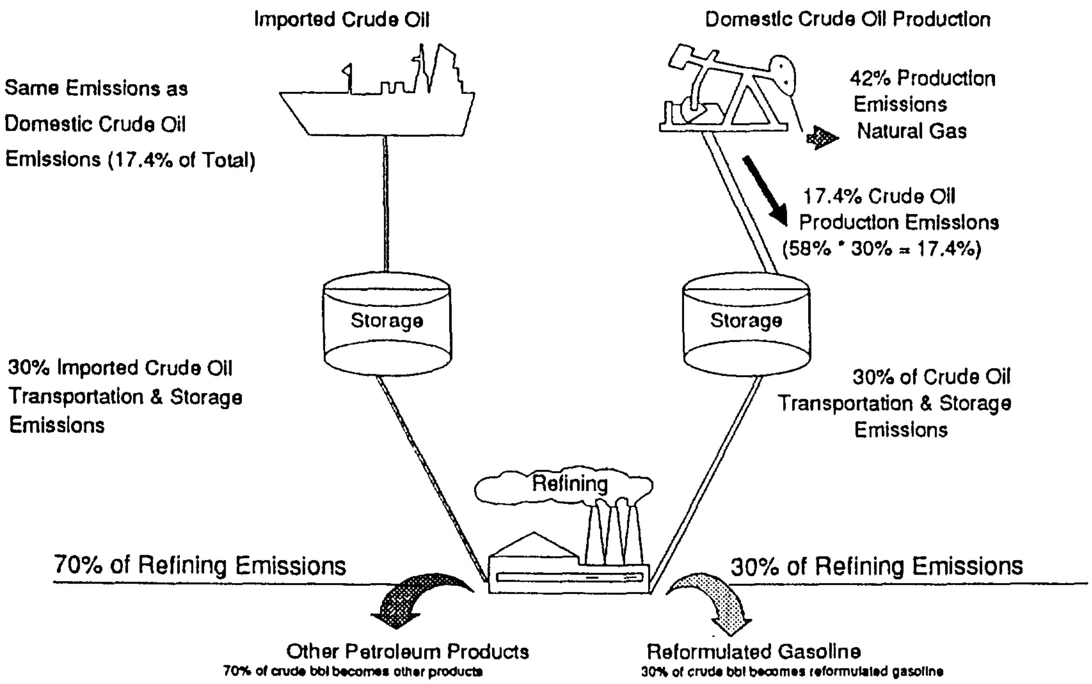


Figure 6 RFG fuel cycle allocation diagram.

Imported crude oil characteristics are added to the fuel production stage. Even with the domestic oil production incentives present in the NES, more than 37% of the oil demanded by refineries will be imported by the year 2010. Estimating foreign oil production characteristics is the best approach to the RFG fuel cycle inventory; however, collecting this information was beyond the scope of this study. The case constructed for the RFG fuel cycle assumes that imported oil is assigned the same production characteristics as domestically produced oil.

Crude Oil Transportation

Domestic crude oil is stored in tankage near the wellhead; then it is transported to crude storage tanks at the refineries. Offshore and Alaskan crude is assumed to be transported by pipeline to a marine tank storage facility; from there it is transported by ocean tanker to coastal refineries or to refinery storage facilities. Current transportation patterns are assumed to be relatively stable throughout the next two decades. National average statistics of the portion of crude oil transported in each mode are used to derive weighted average transportation estimates.

Only the characteristics associated with transporting imported crude oil from the 200-mile economic boundary to the port are included in the fuel cycle study. Transportation characteristics for the beginning of the journey are not included. Imported crude oil is unloaded into storage tanks at existing port facilities. The majority of the imported oil is transported by pipeline to refineries. Because most refineries that depend on imported crude oil are located at ports, imported crude oil is not transported the same distances as domestic crude oil.

The inventory characteristics for crude oil transportation are subject to an allocation assumption described in detail in the following section on refining.

Refining

The petroleum refining industry is the link between crude oil and finished products. The major variables that affect refinery operations with respect to the production of RFG are: (1) crude oil characteristics, (2) crude oil refining technology, and (3) RFG specifications.

The characteristics of the crude oil slate available to refineries will influence U.S. refinery operations. Similarly, the specifications for the major refinery outputs will also affect refinery operations.

For the purposes of this study, a simplifying assumption was made that the U.S. crude refining system can be characterized by two geographical components: one east of the Rocky Mountains that encompasses crude oils processed in the Petroleum Administration for Defense Districts (PADDs) I through IV, and the other west of the Rockies encompassing refining in PADD V. Average crude slate API (American Petroleum Institute) gravities and sulfur contents were forecast for both geographical regions. Two refinery scenarios for the year 2010 were investigated:

- West Coast (PADD V)
- United States less West Coast (PADDs I through IV)

The second step was to define the RFG product specifications. The following list describes the average RFG composition and property characteristics expected.

- Aromatic content: 25% by volume
- Benzene content: 1.0% by volume
- Olefin content: 15% by volume
- Oxygen content: 2.0% by weight
- Summer RVP (Reid vapor pressure): 8.5 psi
- Sulfur content: 100 ppm

The study's approach formulates the gasoline pool to meet these specifications on a nationwide average basis using a plausible scenario based mainly on changes to catalytic reforming operations. MTBE is assumed to be the oxygenate in the U.S. gasoline pool; 11% MTBE corresponds to 2% oxygen. MTBE may be manufactured in a refinery, but for purposes of this study, MTBE is considered a separate input to the gasoline refining process, and no environmental releases associated with its production were calculated. As a result, the fuel cycle inventory provided in this report underestimates total fuel cycle inputs and outputs.

National average refining and blending scenarios are developed based on the two individual refinery scenarios listed previously, along with projected crude production rates, API gravities, sulfur content, and reformulated gasoline product specifications. The scenarios developed assumed that more than 98% of the fuel is produced by complex/integrated refineries. The scenarios proposed are not an attempt to achieve the optimum, but are intended to be plausible on an average nationwide basis. In reality, each refinery will try to achieve an optimum strategy for its individual situation. The refining scenarios evaluated in this study include:

- Reducing reformate severity and therefore reformate volume
- Reducing alkylate and butane volumes in the pool
- Diverting butanes to maximize production of isobutylene, used to make MTBE
- Increasing FCC light olefins production in 2010 (up to that date, the U.S. may be able to import worldwide supplies of isobutylene or MTBE)
- Extracting benzene from reformate
- Eliminating deliberate blending of other aromatics
- Increasing the manufacture of hydrogen to make up for reduced production of catalytic reforming hydrogen

At the same time, the scenarios include increased vacuum distillation and coking volumes to contend with the trend toward heavier crude oils. They also include increased hydrotreating and caustic washing to contend with higher sulfur contents of crude oils.

Environmental releases (air emissions, water releases, and solid wastes) are based on published factors (release/barrel throughput). Environmental releases are calculated by multiplying the annual throughput volumes for each refining step by the emission factors. Major inputs to the refinery include the crude oil, natural gas, electricity, and MTBE for blending with the final gasoline product. Although there are many other chemical inputs to a refinery, they were not included in this study because characterization was difficult and it was expected that the impact on conclusions would be small. Major outputs include the reformulated gasoline stream blended with MTBE and other refinery products that are grouped in this study as other products. These include LPG (liquid petroleum gas), aviation gasoline, benzene, kerosene, jet fuel, heating oil, diesel fuel, fuel oil, coke, and miscellaneous specialty oils and waxes.

All the fuel cycle characteristics for the crude oil production, transportation, and refining stages reported are weighted by the ratio of the gasoline base (gasoline without MTBE) to total refinery product based on the energy content of the product streams. Only 35% of the fuel cycle characteristics associated with crude oil production, transportation, and refining are assigned to RFG. As the characteristics of the crude oil slate and the product slate change, the ratio of gasoline to total refinery output changes. U.S. production of gasoline is projected to fall from 7 million bpd in the year 2000 to 6.3 million bpd in 2010; whereas, crude oil demand is projected to increase from 12.3 million bpd to 13.7 million bpd between 2000 and 2010.

Air emissions are estimated using factors for criteria pollutants, aldehydes, and ammonia obtained from AP-42 (EPA 1985) and modified when appropriate to include control technologies expected to be in place by 2010. The emission factors for greenhouse gases such as carbon dioxide and methane are derived from energy consumption and combustion data.

RFG Distribution

The RFG transportation infrastructure in 2010 is expected to resemble the existing infrastructure because major changes are not considered in the NES. RFG can be transported via pipeline, barge, rail, and truck from the refinery to bulk terminals or marine terminals. From bulk terminals the fuel is usually transported to bulk plants in local metropolitan areas using tanker trucks. Trucks are used to transport the fuel from bulk plants to retail outlets. Fuel consumption for transporting gasoline is reported for the nation as a whole. Thus, it is not necessary to develop detailed estimates of how much gasoline is transported by each mode for any given distance. The lack of distances could be confusing, but keep in mind that if national estimates of fuel use in gasoline transportation are available, they are preferred to detailed modeling of a complex system. The assumption is made that the percentage of fuel that travels through the various transportation modes remains constant.

Number 2 diesel is assumed to be the only fuel used in trucks, rail, and inland barges. Number 6 diesel is assumed to be the only fuel used in ocean tankers and barges. Pipeline pumps and pumps at storage facilities are assumed to be all electrically driven.

The primary sources of emissions are vehicle emissions, primarily from rail and trucks because pipeline pumps are assumed to be electric. Vapor recovery controls are assumed to be universally employed with an recovery efficiency of 95%. Vapor recovery systems are assumed to be used at the pumps in all retail stations.

FUEL END USE CHARACTERISTICS

E95 and RFG are consumed in light-duty, spark-ignition passenger vehicles that represent technology available in 2010. Fuel composition and vehicle performance are estimated using an engineering analysis based on the technical literature. The emission values are generated from published EPA data. Changes in emission levels expected from vehicles using ethanol fuels are projected from identified changes in emissions from vehicles using reformulated gasoline. Ethanol vehicle performance is based on a theoretical analysis of the physical and chemical property differences between RFG and ethanol fuels. The theoretical analysis is then supported through a comparison with empirical data on actual engine performance measurements presented in the literature.

Vehicle emissions from RFG are based on a scenario of proposed CAAA Tier II standards being met by 2010. Evaporative emission standards have not been proposed by the EPA, and therefore, they are projected to equal the exhaust VOC levels as currently observed. Carbon dioxide and sulfur dioxide emissions are based on fuel carbon and sulfur content, respectively, and on projected fuel economy for each fuel. The fuel economy projections are based on NES estimates for a compact vehicle. Fuel economy projections for RFG are based on changes in fuel energy content resulting from the hydrocarbon distribution in an RFG.

E95

By the year 2010, fully optimized engines for ethanol fuels should be available. They could take the form of dedicated-fuel, high-compression engines designed to run specifically on E85 or E95, or they could be variable-fuel, variable-compression engines with highly sophisticated engine control systems able to optimize engine performance for a variety of fuels. The theoretical analysis suggests a 15% efficiency advantage for ethanol over gasoline, including the effect of greater tank and fuel weight. On a proportional basis this would translate to a 14% advantage for E95. Insufficient data are available to confirm these percentages experimentally. On a constant compression ratio basis the theoretical advantage for ethanol would be 7%. The available data indicates an assumption that a 15% advantage for an optimized engine is a reasonable estimate of future potential. This theoretical value is assumed as the correct measure of potential by 2010. Because of its lower energy density, light-duty passenger vehicles are assumed to get 28.25 miles per gallon on E95 and 35.6 miles per gallon on reformulated gasoline.

RFG

The CAAA requires that RFG be sold in the nine worst ozone nonattainment areas starting in 1995. States or cities can also elect to use RFG to satisfy local environmental goals. The NES projects that RFG will replace conventional gasoline by the year 2000. Future vehicle efficiency projections are based on the NES projections of new-car efficiency ratings for the year 2010 of 37.1 miles per gallon based on 1990 gasoline. The estimated energy density of RFG containing 15% MTBE, plus enough added alkylate to replace aromatics and olefins, is approximately 4% less than the energy density of 1990 gasoline. Converting the NES data to miles per million Btu yields a fleet average mileage projection of 35.6 miles per gallon in the year 2010 using RFG. This corresponds to 244 miles per million Btu.

ALLOCATION METHODOLOGY

Fuel cycle characteristics for a stage or activity were divided among the co-products of that stage or activity in three areas: crude oil production, crude oil refining, and ethanol production. In addition, prior activities were also subjected to the allocation. Analysts assigned inventory characteristics on the basis of the ratio of energy in the final product compared to the energy of the total outputs.

Co-production of Crude Oil and Natural Gas

Natural gas is often produced with crude oil. It is referred to as associated gas. If all the inventory characteristics of producing crude oil are assigned to crude oil, the natural gas produced is "free" to society; it has no costs associated with its production. Indeed, this is how it is viewed by some analysts. The RFG case assumes that the inventory associated with crude oil production is divided, between the natural gas and crude oil produced. Crude oil is assigned 58% of the production characteristics and natural gas is assigned the remaining 42%.

Co-production of Multiple Refinery Products

Crude oil is transformed into RFG and numerous other products including jet fuel, fuel oil, fuel gas, diesel, propane, petrochemicals, coke, and asphalt. In the RFG case, the refinery characteristics are divided between RFG and "all other products" based on a Btu equivalent value of total output. In the year 2010, 30% of the refinery emissions are assigned to RFG.

The characteristics of the crude oil production and transportation stages are similarly allocated. The remaining crude oil production, transportation, and refining inventory characteristics are assigned to "other petroleum products." Therefore, only 30% of the crude oil transportation emissions are assigned to RFG; only 17.4% of the crude oil production inventory is reflected in the RFG fuel cycle (0.58×0.30).

Biomass-Ethanol Conversion Process

The biomass conversion facility produces two products: E95 and electricity. The characterization of the activities that produce, transport, and convert biomass need to reflect only that portion that actually contributes to ethanol production, rather than electricity. Therefore, the results reflect an allocation of the characteristics of feedstock production, transportation, and conversion based on the ratio of energy content in the ethanol to that of the total products. Each regional case is slightly different, because different feedstocks yield different proportions of ethanol and electricity. The average of the allocation characteristics of the five 2010 cases is 80% to ethanol, 20% to electricity.

FINDINGS

The discussion of results focuses on the gaseous, solid, and liquid emissions because the major issues revolving around fuel use today are their environmental implications.[2a] The data inventories of all of the activities involved with producing fuel to power a car for a common distance are aggregated into totals for each stage of the fuel cycle and for the fuel cycle as a whole. Any common basis may be used. In this report, emissions are reported on a grams or milliliters per light-duty passenger vehicle mile traveled (VMT) basis.

E95 AND RFG FUEL CYCLES

There is little difference in emission characteristics from each stage of the five E95 fuel cycles (Table 3). The differences that do occur among the E95 cases are caused by different types of feedstocks and different feedstock transportation characteristics.

CO emissions are 6 to 8% higher for E95 compared with RFG. NO_x emissions for E95 range from 97 to 104% of NO_x emissions from RFG, and SO_2 emissions are 60 to 80% lower for E95 fuels. Particulate emissions are 100 to 150% higher for E95, and VOC emissions (excluding biogenic emissions) are 13 to 15% less than RFG. E95 produces less than 10% of the CO_2 emissions that RFG produces. All of the emissions associated with producing and transporting feedstocks and producing fuel have been allocated between the various products as described earlier.

Carbon Monoxide Emissions (CO)

An average of 92% of the CO emissions from the E95 fuel cycles and 98% of the CO emissions from the RFG fuel cycle come from the passenger vehicle in the end-use stage (Figure 7). Vehicle emissions are 1.7 g CO per mile for both fuels, based on the

Table 3 **E95 and RFG fuel cycle emissions (milligrams per VMT)**

Emission	Fuel	End Use	Fuel Distrib.	Fuel Prod.	Feedstock Transport.	Feedstock Prod.	Total
CO	E95	1695.9	2.2	99.4[a]	7.2	43.7	1848.4
	RFG	1700.0	2.7	7.3	9.1	6.4	1725.5
NO_x	E95	199.4	6.5	68.3[a]	11.1	43.7	329.0
	RFG	199.6	4.5	65.3	20.9	37.2	327.5
PM	E95	0.0[b]	0.1	4.5[a]	0.1	4.5	9.2
	RFG	0.0[b]	0.2	2.1	1.0	0.7	4.0
SO_2	E95	3.7	0.2	21.1[a]	0.8	2.0	27.8
	RFG	40.0	0.3	4.0	0.9	4.5	85.6
CO_2[c]	E95	15.1	0.9	3.6[a]	2.5	5.8	27.8
(grams)	RFG	243.0	1.0	26.9	4.1	14.7	289.7
VOC[d]	E95	159.7	17.2	18.8[a]	2.0	10.1	207.8
	RFG	179.6	35.4	3.6	11.8	12.7	243.1
Wastewater	E95	n/a	n/a	490.0[a]	n/a	0.0	490.0
(ml)	RFG	n/a	n/a	57.0	n/a	91.0	148.0
Solid	E95	n/a	n/a	16,010.0[a]	n/a	0.0	16,010.0
Wastes	RFG	n/a	n/a	544.0	n/a	91.0	635.0

[a] Includes gasoline fuel cycle emissions for gasoline added to ethanol in this stage.

[b] Particulate emissions from passenger vehicles not available for E95 or reformulated gasoline.

[c] Fossil CO_2, does not include CO_2 sequestered in biomass or released from fermentation or ethanol combustion.

[d] VOC totals, excluding biogenic emissions.

assumption that vehicles and fuels will be designed for cars to ensure that the proposed Tier II standards of the CAAA are met. Technologies, such as improved catalytic converters and other pollutant traps, could benefit both fuels.

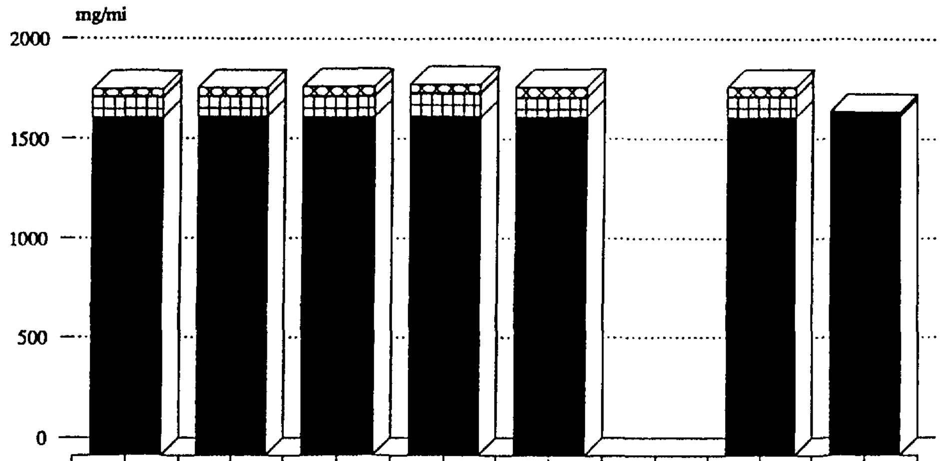
E95 fuel cycles produce 6 to 8% more CO than the RFG fuel cycle because of the combustion of solid wastes in the boiler of the ethanol production facility. Refineries were assumed to purchase excess power needs, and the emissions associated with that electricity are not included in the base cases; however, they are included in the electricity sensitivity cases. Although biomass combustion is perceived as a mature technology, many technological advances in boiler efficiency are under examination by NREL and others. More efficient biomass boilers and/or improved emission controls could be developed by the year 2010, which could diminish boiler emissions.

Nitrogen Oxides Emissions (NO_x)

There is no significant difference in the amount of NO_x produced by either fuel cycle; the emissions from the average E95 fuel cycle and the RFG fuel cycle are roughly the same for each stage (Figure 8). NO_x emissions for crude oil transportation are higher than those of biomass transportation because of the longer distances involved.

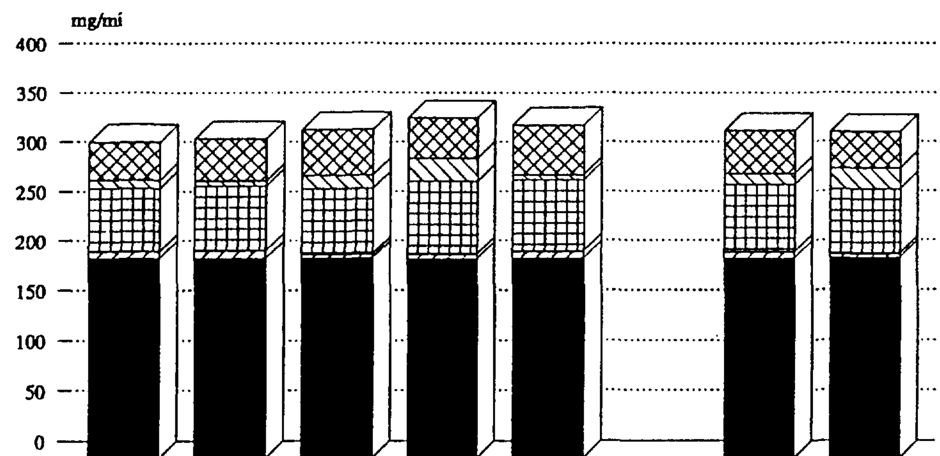
The passenger vehicles, in the end-use stage, produce about 61% of the NO_x emissions in both fuel cycles. Vehicle emissions were 0.2 g NO_x per mile for both fuels. Analysts assumed that both fuels and vehicles are designed to meet the proposed Tier II standards of the CAAA.

Fuel production is the second largest NO_x source for both fuel cycles, producing 20% of the total emissions. NO_x is produced during the combustion of the waste biomass in the ethanol plant's boilers and the combustion of petroleum by-products in the refinery.



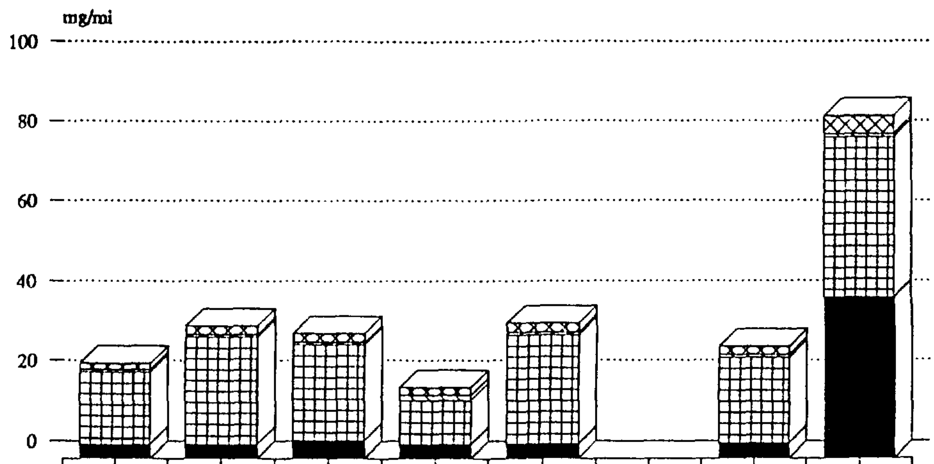
	E95 Tifton	E95 Peoria	E95 Rochester	E95 Portland	E95 Lincoln		E95 Avg	RFG 2010
Feedstock Production	38.4	42.4	46.1	41.2	50.4		43.7	6.4
Feedstock Transport	8.3	5.2	8.2	9	5.3		7.2	9.1
Fuel Production	95.2	95.5	97	117.1	92.1		99.4	7.3
Fuel Transport	1.8	2.7	1.8	1.8	2.7		2.2	2.7
Fuel End Use	1693.7	1697.4	1697.4	1693.7	1697.4		1695.9	1700

Figure 7 Fuel cycle emissions of carbon monoxide.



	E95 Tifton	E95 Peoria	E95 Rochester	E95 Portland	E95 Lincoln		E95 Avg	RFG 2010
Feedstock Production	38.4	42.4	46.1	41.2	50.4		43.7	37.2
Feedstock Transport	8.3	5.2	13.4	23.2	5.3		11.1	20.9
Fuel Production	64	65.5	66.3	73.5	72.2		68.3	65.3
Fuel Transport	7.3	8.2	4.5	5.4	7.3		6.5	4.5
Fuel End Use	199.6	199.6	199.6	198.7	199.6		199.4	199.6

Figure 8 Fuel cycle emissions of nitrogen oxides.



	E95 Tifton	E95 Peoria	E95 Rochester	E95 Portland	E95 Lincoln		E95 Avg	RFG 2010
Feedstock Production	1.5	2.2	2.2	1.9	2.3		2	4.5
Feedstock Transport	0.7	0.7	0.7	1.3	0.8		0.8	0.9
Fuel Production	17.8	26.6	23.7	10.7	26.9		21.1	39.9
Fuel Transport	0	0	0.2	0.3	0.3		0.2	0.3
Fuel End Use	3.6	3.6	4.4	3.4	3.5		3.7	40

Figure 9 Fuel cycle emissions of sulfur dioxide.

Analysts assumed that ammonia injection is used to control NO_x emissions from the ethanol plant's boiler. The NO_x emissions from the boilers are a combination of thermal NO_x, and the combustion of the nitrogen in the protein portion of the solid waste stream.

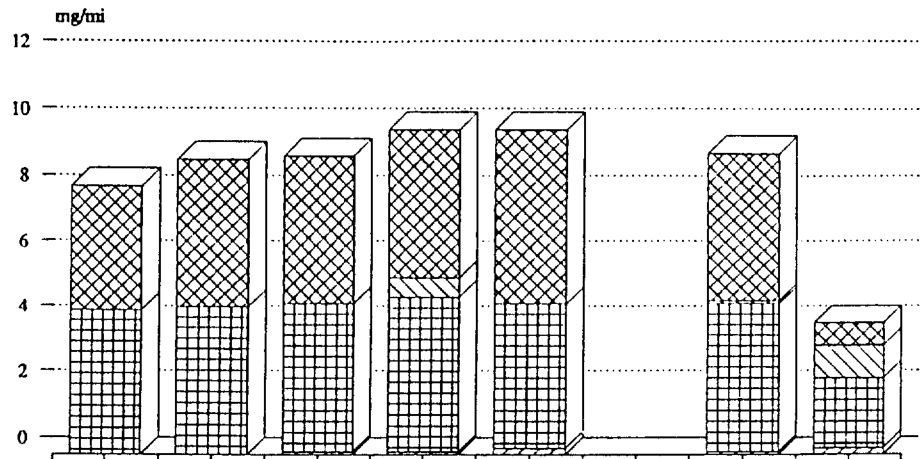
The other major NO_x source is feedstock production. NO_x emissions are produced by farm vehicles using diesel fuel. Farm vehicle use is correlated with biomass yields (lower yields require more land under cultivation and more diesel fuel, and the types of biomass grown) and some management and harvesting activities are more energy intensive than others. Because land quality affects biomass yields and the management practices required, it is difficult to draw any conclusions about specific crops having a major influence on the level of NO_x emissions. The variability in NO_x emissions for the feedstock transportation stage is due to different modes of transportation: truck, rail, and barge. NO_x emissions are higher when rail and barge are used to move feedstocks (Portland, Oregon and Rochester, New York, respectively). The other cases relied exclusively on truck transportation.

Sulfur Dioxide Emissions (SO_2)

SO_2 is produced from two sources: transportation vehicle emissions (diesel-fueled and passenger) and stationary sources, such as the conversion facility and the refinery (Figure 9). Even if the level of sulfur in RFG is reduced from 350 to 50 ppm—reducing emissions in the end-use stage by 86%—total fuel cycle SO_2 emissions from the RFG fuel cycle will still exceed those from E95 fuel cycles.

Pure ethanol does not contain sulfur; however, the denaturant gasoline contains sulfur. Since the denaturant represents only 5% by volume, E95 provides a significant reduction in SO_2 emissions from passenger vehicle exhaust over RFG.

More than 75% of the SO_2 produced in the E95 fuel cycles results from combusting wastes at the conversion facility. The proteins in biomass contain sulfur, which is the



	E95 Tifton	E95 Peoria	E95 Rochester	E95 Portland	E95 Lincoln		E95 Avg	RFG 2010
Feedstock Production	3.8	4.5	4.5	4.5	5.3		4.5	0.7
Feedstock Transport	0	0	0	0.6	0		0.1	1
Fuel Production	4.4	4.5	4.5	4.7	4.4		4.5	2.1
Fuel Transport	0	0	0.1	0.1	0.2		0.1	0.2
Fuel End Use	0	0	0	0	0		0	0

Fuel End Use; Fuel Transport; Fuel Production; Feedstock Transport; Feedstock Production

Figure 10 Fuel cycle emissions of particulate matter.

source of SO_2 emissions from the boiler. Most of the regional variation in SO_2 production in the E95 fuel cycles is the result of differences in the protein content of the feedstocks used. The Portland, Oregon, conversion facility produces the least SO_2 because it uses exclusively wood feedstocks that do not contain high levels of protein; the Lincoln, Nebraska, plant produces the most SO_2 because it uses exclusively grass feedstocks that contain relatively high levels of protein. SO_2 emissions from the conversion facility boilers at other facilities fall between these extremes because feedstocks are composed of mixtures of wood and grass biomass.

Sulfur contained in the crude oil is the source of SO_2 emissions from the refinery. Refineries may be required to reduce their SO_2 emissions in the future, resulting in lower SO_2 emissions than presented in this study.

Feedstock production and transportation activities create SO_2 from diesel fuel used in tractors, trucks, and other equipment. Reducing the sulfur content of diesel will affect the total SO_2 emissions from both fuel cycles in direct proportion to the amount of diesel fuel consumed in both fuel cycles.

Particulate Matter Emissions (PM)

Approximately half of the particulates produced in the E95 fuel cycles are tailpipe emissions from diesel-fueled farm and feedstock transportation vehicles; the other half are emissions from the ethanol conversion facility (Figure 10). In the RFG fuel cycle, over 50% of the particulates are produced from the refinery, followed by another 25% from crude oil transportation (diesel use in tankers, railroads, etc.); the remainder is produced from production and processing equipment at the wellhead and RFG distribution. Data on the quantity and composition of particulates from passenger vehicles fueled by E95 or RFG were not available and therefore are not included in the total emission levels presented.

	E95 Tifton	E95 Peoria	E95 Rochester	E95 Portland	E95 Lincoln		E95 Avg	RFG 2010
Feedstock Production	9.2	9.7	10.4	9.7	11.3		10.1	12.7
Feedstock Transport	2.3	1.5	2.2	2.6	1.5		2.02	11.8
Fuel Production	18	18.6	17.8	21.5	18		18.8	3.6
Fuel Transport	17.2	17.2	17.2	17.2	17.2		17.2	35.4
Fuel End Use	159.7	159.7	159.7	159.6	159.7		159.7	179.6

Fuel End Use, Fuel Transport, Fuel Production, Feedstock Transport, Feedstock Production

Figure 11 Fuel cycle emissions of volatile organic compounds.

The particulate emissions from the conversion facility are divided equally between boiler fly ash emissions and dust from the feedstock handling and preparation activities. The fly ash emissions are a function of the quantity and composition of the material fed to the boiler.

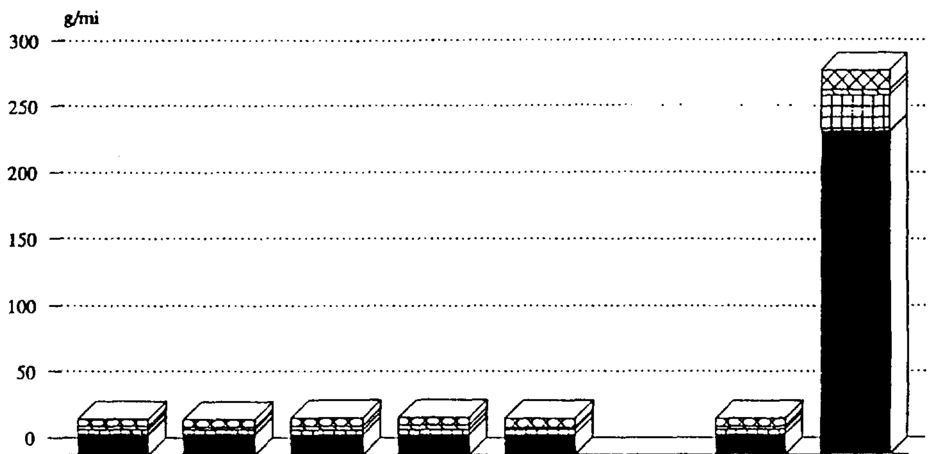
Particulate emissions from feedstock and fuel transportation are positive but very low. In most cases, these estimates are shown as zero. The exception of the E95 Portland fuel cycle is caused by transporting biomass feedstock by rail, which is responsible for the relatively high levels of particulate emissions in the feedstock transportation stage.

If airborne soil erosion, fertilizers, and pesticides are included in the accounting of particulates, total particulate emissions in the E95 fuel cycles increase dramatically. An impact analysis is required to determine if some or all of these airborne farm emissions would have occurred in the absence of a biomass-ethanol industry, and if so, how much of these emissions are the direct result of the biomass-ethanol industry.

Volatile Organic Compound Emissions (VOC)

VOC emissions were divided into two source categories: (1) biogenic VOC emissions produced by growing plants, and (2) nonbiogenic VOC emissions produced during the use or combustion of fossil fuels and volatile chemicals. This allows us to compare the quantities of nonbiogenic VOC emissions of the two types of fuel cycles—E95 and RFG. RFG fuel cycles do not produce any biogenic VOC emissions.

Approximately 75% of the nonbiogenic VOC emissions produced from the E95 and RFG fuel cycles are evaporative and exhaust emissions from the passenger vehicles used in the end-use stage (Figure 11). Exhaust emissions were assumed to be identical for both fuels—0.09 g per mile. Evaporative engine losses were less for E95 (0.07 g per mile) compared to RFG (0.09 g per mile). This difference caused end-use emissions from



	E95 Tifton	E95 Peoria	E95 Rochester	E95 Portland	E95 Lincoln		E95 Avg	RFG 2010
Feedstock Production	5.12	5.654	6.1	5.475	6.701		5.81	14.697
Feedstock Transport	2.56	1.627	2.901	3.607	1.656		2.47	4.082
Fuel Production	3.612	3.612	3.612	3.612	3.612		3.612	26.944
Fuel Transport	0.998	1.089	0.635	0.817	0.907		0.889	0.998
Fuel End Use	15.125	15.125	15.125	15.125	15.125		15.124	243.039

Figure 12 Fuel cycle emissions of carbon dioxide.

dedicated passenger vehicles using E95 to be 11% less than emissions from vehicles using RFG.

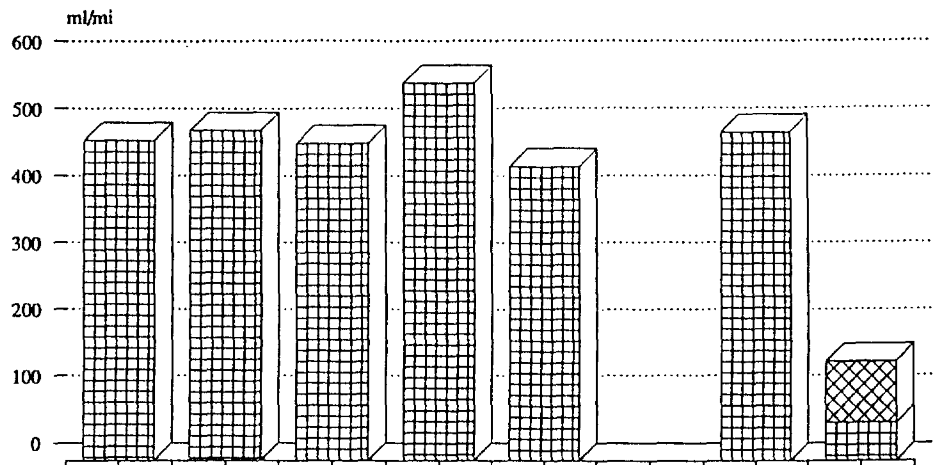
The remaining VOC emissions are produced from the combustion of diesel fuel in equipment used to produce and transport feedstocks and fuels. The biomass conversion processes also produce significant amounts of VOCs from the boilers.

If biogenic VOC emissions are included in the VOC accounting framework, total VOC emissions in the E95 fuel cycles increase 600 to 1600% depending on the proportion of trees produced in the biomass feedstock mix. Deciduous trees produce nearly 10 times more biogenic VOCs than any other agricultural crop except corn.[5] Analysts assumed that herbaceous biomass crops did not produce biogenic VOC emissions, although it is likely that these emissions will be produced in small quantities. The extent that tree crops displace corn and other crops will determine the net changes in localized biogenic VOC emissions. This net analysis should be undertaken in the future.

Not enough data exist to completely define the components of the biogenic and nonbiogenic VOC emissions in sufficient detail to perform ozone impact studies. Each specific VOC compound has a different reactivity and chemical signature in the atmosphere. Some decompose rapidly and others have complex reaction chains. The differences in the composition of VOC emissions will influence the timing, persistence, and impacts of ozone creation in a locality.

Carbon Dioxide Emissions (CO_2)

E95 fuel cycles produce an average of 27.9 g net CO_2 per VMT. The RFG fuel cycle produces 290 g CO_2 (Figure 12). CO_2 emissions from the E95 fuel cycles are positive because diesel vehicles that burn fossil fuel are used in transportation, farming, and other minor activities, and because 5% of E95 consists of gasoline. Thus, a portion of the RFG fuel cycle is added to the E95 fuel cycle, reflecting the fuel cycle emissions associated with the denaturant. Displacing gasoline with ethanol fuels is a policy option



	E95 Tifton	E95 Peoria	E95 Rochester	E95 Portland	E95 Lincoln		E95 Avg	RFG 2010
Feedstock Production	0	0	0	0	0		0	91.5
Feedstock Transport	0	0	0	0	0		0	0
Fuel Production	478.5	493.8	474.3	563.9	439.6		490	56.5
Fuel Transport	0	0	0	0	0		0	0
Fuel End Use	0	0	0	0	0		0	0

Figure 13 Fuel cycle emissions of wastewater.

that appears to have a substantial impact on transportation-related CO_2 emissions. More than 90% of the CO_2 emissions associated with RFG can be avoided by replacing gasoline with E95.

Wastewater Emissions

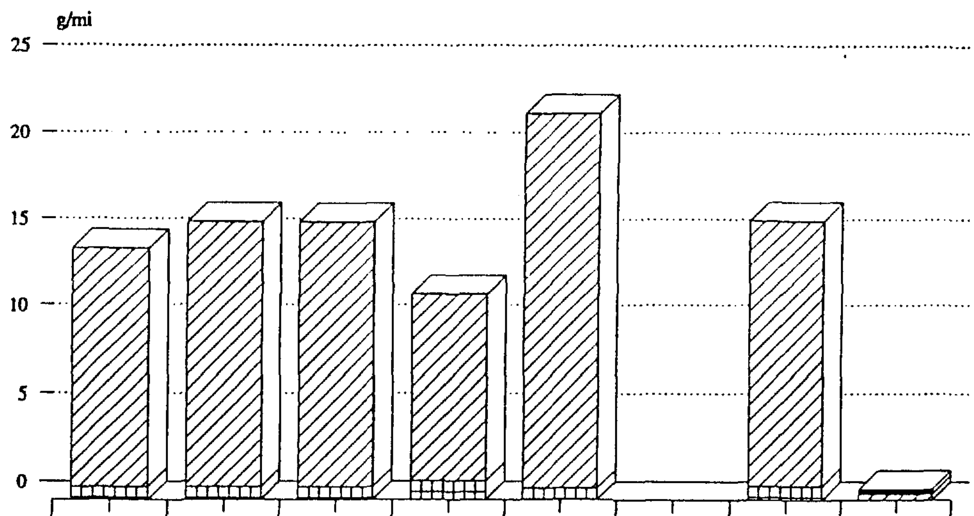
The E95 fuel cycles produce 490 milliliters (ml) of wastewater per VMT, on average, compared with only 148 ml per VMT in the RFG fuel cycle (Figure 13). The wastewater produced in the E95 fuel cycle comes from the conversion facility, except for the water that is reflected in the 5% gasoline contained in E95. The wastewater in ethanol plants could be reduced by as much as 60% with more sophisticated water recycling designs.

The process water from ethanol production can be treated by city sanitation plants to produce potable water. The wastewater stream is an optimal environment for growing organisms and as such is suited to other agricultural uses.

Most of the wastewater produced in the RFG fuel cycle is formation water that is produced during oil production. It commonly contains salts, metal, oil, radionuclides, and other hazardous materials. Most of the formation water is reinjected into the oil reservoir or other geological zones. The formation water reinjected and the process water used for enhanced oil recovery (EOR) is not considered wastewater. If they were, estimated wastewater produced during crude oil production would be approximately 20 times higher than the total reported here.

Solid Waste Emissions

The E95 fuel cycles produce 11.7 to 22.2 g solid waste per VMT. Of this waste, about half is gypsum produced from neutralizing sulfuric acid used in the pretreatment process, and half is the ash remaining after the nonfermentable residues are combusted (Figure 14). If another method of biomass pretreatment could be used that did not require acid prehydrolysis, solid waste production could be cut by half. The solid waste produced by



	E95 Tifton	E95 Peoria	E95 Rochester	E95 Portland	E95 Lincoln		E95 Avg	RFG 2010
Hazardous Solids	0.022	0.022	0.022	0.022	0.022		0.022	0.272
Benign Solids	13.582	15.13	15.13	10.592	21.489		15.184	0.363
Sludge	0.753	0.744	0.744	1.095	0.678		0.803	0

Figure 14 Fuel cycle emissions of solid wastes.

an ethanol plant is not considered hazardous. Currently, biomass ash from combustion boilers is in demand as a landfill amendment to control acidity.

Approximately half of the 0.64 g solid waste per VMT produced in the RFG fuel cycle is considered dangerous: hazardous, toxic, carcinogenic, etc. Future waste reduction technologies, high-temperature combustion, and other alternatives are being explored that could reduce petroleum industry wastes.

Impact of Adding the Secondary Emissions Associated with Electricity

If one assumes that the by-product electricity sold by the ethanol plant offsets or partially eliminates the need for a utility company to produce electricity, then the avoided emissions can be viewed as emission "credits" for the electricity produced from the ethanol plant. Similarly, when electricity is consumed in a fuel cycle, the emissions associated with producing that electricity should be included in the fuel cycle. For the six cases discussed previously, NO_x, SO_2, CO_2, particulates, and solid waste emissions per kilowatt-hour (kwh) were subtracted as credits when electricity was produced and added to the fuel cycle inventories (debits) when it was consumed. Table 4 shows the incremental changes in the base cases caused by the sensitivity analysis.

The ethanol fuel cycles are regional. Some stages of the RFG fuel cycle have activities in them that are regionally concentrated (like refining and oil production), whereas other stages are national in character (fuel distribution). Utilities also have regional characteristics, depending on local resource endowments and environmental air quality regulations. Therefore, analysts estimated regional electricity generation emissions characteristics for each region.

Characteristic electricity generation emissions are added to the fuel cycle where electricity is consumed and credited against emissions where electricity is produced. For crude oil production, transportation, and refining, the activities are apportioned to various regions, depending on where they occur today. Thus, the emission debits and credits for

Table 5 **Total energy requirements**

	E95	RFG 2010
Process Energy Inputs (Btu VMT)		
Feedstock production	167.8	34.8
Feedstock transportation	31.3	121.5
Fuel production	81.0	190.7
Fuel distribution	150.7	194.9
Subtotal process energy inputs	430.8	541.9
Feedstock Energy Inputs and MTBE (Btu VMT)		
Biomass feedstock	4659.6	n/a
Crude oil feedstock	245.4	3105.8
MTBE	0	293.5
Subtotal feedstock energy and MTBE	4905.0	3399.3
Fuel Including Fuel Additives, Ethanol or MTBE (Btu VMT)		
End-use fuel energy value	2752.0	3108.0
Energy Ratios		
Nonfeedstock inputs/fuel output	0.157	0.174
Total fossil inputs/fuel output	0.246	1.27
Total inputs/fuel output	1.94	1.27

(Table 5). Throughout the energy analysis, lower heating values are assumed. Biomass heating values are estimated on a dry weight basis. The heat rate of 10,400 Btu per kWh for electricity captured the inefficiencies of electricity production. Energy embodied in fertilizer, chemicals, and electricity is included.

Process Energy Requirements

Process energy is energy required to operate equipment in each of the four stages of the fuel cycle: feedstock production, feedstock transportation, fuel production, and fuel distribution. The end-use stage is not included in this category since the only operation that occurs in that stage is the combustion of the fuel to provide mobility; it is shown below under *Fuel including fuel additives.* Process energy does not include feedstocks (not even the feedstocks consumed to provide process energy in refineries and ethanol production facilities, e.g., shrinkage) or fuel additives such as MTBE.

E95 fuel cycles are slightly more efficient than RFG, consuming fewer Btus of process energy inputs per Btu of output. On the whole, the differences in process energy consumed per Btu of energy output is relatively similar; however, some interesting differences among the stages are noteworthy.

Feedstock production is almost three times more energy intensive (Btu energy consumed per Btu energy feedstock produced) for E95 than for RFG. This is the result of producing a relatively diffuse, low-Btu fuel. Half of the energy required in feedstock production for E95 is used to fuel farm equipment (diesel) and half is embodied in the production of nitrogen fertilizer.

The energy consumed in feedstock transportation is four to five times higher for RFG than for ethanol fuels on a basis of Btu of energy consumed per Btu of feedstock moved. Nearly 60% of the energy requirements in crude transportation are electricity inputs for pipeline transportation. The remainder is diesel for tanker, barge, rail, and truck transportation. Crude oil is transported longer distances (average 615 miles) compared with biomass (26 to 48 miles), which offsets the benefits of moving a more condensed energy product.

of the feedstock into a condensed liquid fuel and using a low-Btu boiler fuel in the ethanol plant.

In Table 5, only a fraction of total energy inputs are shown in each of the fuel cycles—the portion required to produce, transport, and convert feedstocks into liquid fuel. The allocations discussed earlier have been applied.

CONCLUSIONS AND DISCUSSION

This study presents data on environmental emissions produced by two fuel cycles: E95 and RFG, which can be used to support impact studies, cost/benefit studies, and economic analyses. Providing the best possible estimates of the quantities of emissions created by an industry is necessary to conduct credible and useful studies of environmental impacts and their benefits or costs. This study has focused on providing quality information for further analysis.

The results of this work can be used to evaluate limited policy objectives. If decision makers need to reduce a particular emission, such as carbon dioxide, then this report provides information that can be used to evaluate the benefits of substituting gasoline with E95 and RFG. For example, this report indicates that E95 reduces CO_2 emissions, which could reduce or forestall global warming, if substituted for RFG. However, we have only quantified CO_2, and not necessarily included other greenhouse gases such as nitrous oxide and methane. The information summarized here and described in more detail by Tyson[4] is a powerful tool, but not the only tool needed to evaluate policy options for transportation.

Each fuel examined in this report has some advantages that the other fuels do not; e.g., reduces CO, VOC, or other emissions. No one fuel examined can be characterized as better or worse than its alternatives based on the results of this study alone because benefits of reducing some emissions are offset by increases in other emissions. Future analysis of economic, environmental, and health impacts of the emissions volumes reported are required to support this type of conclusion.

The analysis revealed a number of interesting results:

- Vehicle emissions create the bulk of most of the gaseous emissions.
- Increasing use of E95 is a promising option for reducing CO_2 emissions from the transportation sector because E95 fuel cycles produce less than 10% of the CO_2 emissions produced by the RFG fuel cycle.
- When emissions from electricity generation are added to the fuel cycle analysis, E95 fuels produce significantly less NO_x, SO_2, particulates, and CO_2 emissions than RFG.
- Ethanol fuels can extend our fossil fuel resources in the transportation sector until a permanent solution is found for our dependency on petroleum, since ethanol fuels require fewer fossil fuel resources than RFG.
- Assumptions concerning technology performance, particularly emission control equipment, environmental regulation, and allocation assumptions, heavily influence the results of this study.

Vehicle emissions dominated total fuel cycle gaseous emissions in all the fuel cycles. Improvements in engine performance, catalytic converters, and other vehicle emission controls will benefit both fuels. CAAA standards for vehicle emissions will play a central role in determining the emission characteristics of the fuel cycles. Owing to the lack of data on ethanol fuel emissions, many emission estimates are based on the assumption that fuel and auto manufacturers will design systems to meet regulations. Thus, these regulations are critical focal points of the analysis.